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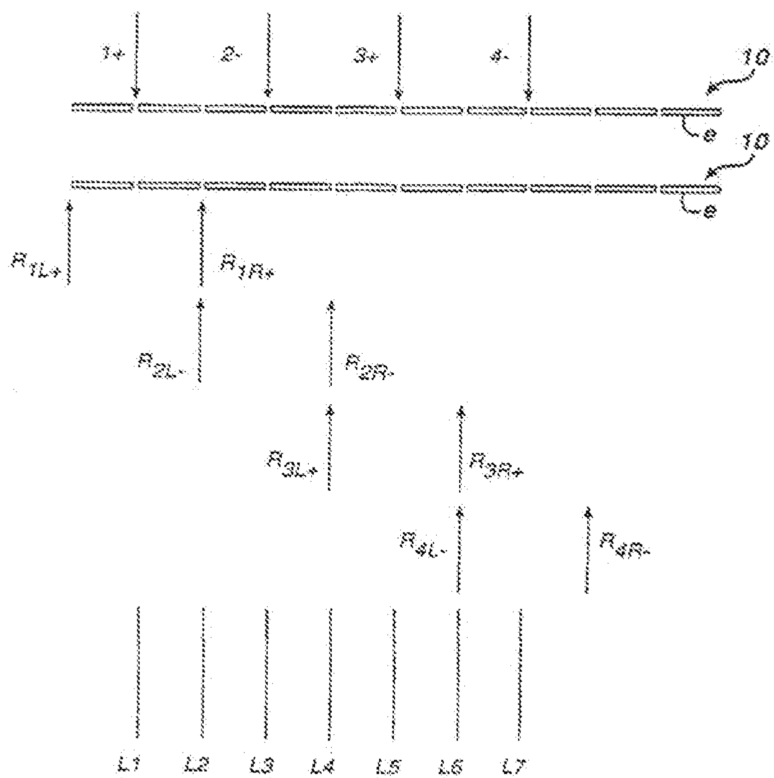
(57) Abstract

An ultrasonic diagnostic imaging system and method are provided for producing r.f. interpolated image lines with reduced susceptibility to motion artifacts. A multiline beamformer receives multiple scanlines in response to each transmitted beam. Image lines are produced by r.f. interpolation of these multiline scanlines in a temporally consistent manner. In an illustrated embodiment, each image line is produced by the interpolation of scanlines produced in response to at least two transmitted beams. In a preferred embodiment the interpolated image lines are produced by a [1 2 1] lateral filter.



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High frame rate ultrasonic diagnostic imaging systems with motion artifact reduction.

This invention relates to ultrasonic diagnostic imaging systems and, in particular, to ultrasonic diagnostic imaging systems capable of producing high frame rate ultrasonic images with reduced motion artifacts.

U.S. Patent 5,706,819 describes a signal processing technique which separates fundamental and harmonic signal components in received ultrasonic echo signals. This technique, known in ultrasound as "pulse inversion," is a two pulse technique in which two pulses of opposing polarity (phase) are successively transmitted to the same location in the body. Echoes are received following each transmission in which fundamental signal components are out of phase due to the opposing polarity of the transmit pulses, but the higher order harmonic signal components, being quadratic in nature, are not. Summing the two echoes will cancel the opposing fundamental components and reinforce the harmonic components, leaving a cleanly separated harmonic signal without the need for conventional filters. Subtracting the two echoes will have the opposite result, canceling the harmonic signal components and reinforcing the fundamental (linear) signal components. In a similar manner, subtraction leaves a cleanly separated fundamental echo signal.

Pulse inversion is a two pulse technique, however, meaning it is necessary to scan each acoustic line twice in order to form a single image. This means that the time required to acquire all of the scanlines of an image is approximately doubled as compared to conventional single pulse imaging. The time to acquire all of the scanlines of an image frame determines the frame rate of display, which will approximately halve with a two pulse technique. It is desirable to have as high a frame rate as possible so that real-time imaging is produced which shows tissue motion smoothly and with little interframe discontinuity as a scanhead is moved when surveying a patient's anatomy.

In a concurrently filed application it is shown how pulse inversion harmonic imaging can be carried out at a high frame rate of display and a high line density. In one embodiment of that inventive technique transmit pulses of opposing polarity (phase) are transmitted along transmit scanlines at adjacent positions in the image field and multiple scanlines are received in response to each transmitted beam. Received scanlines from opposite polarity pulses are combined to produce harmonic images at a high frame rate of

display. By combining received scanlines in a temporally consistent manner, motion artifacts are reduced. In the present invention, this principle is applied to reduce motion artifacts when performing r.f. interpolation of multiline scanlines. The inventive system employs a multiline beamformer which receives and forms multiple received scanlines in response to a single beam transmission. Interpolated scanline image data is produced by interpolating temporally different scanline data for each image line. The image data is then used to form an ultrasonic image. The scintillation effect of motion is eliminated by the use of temporally different scanline data to form each image line.

In the drawings:

FIGURE 1 illustrates a pulse inversion scanning technique of the present invention which produces a high line density image;

FIGURE 2 illustrates a pulse inversion scanning technique of the present invention which produces ultrasonic images at a high frame rate of display;

FIGURE 3 illustrates a variation of the pulse inversion scanning technique of FIGURE 2;

FIGURES 3A-3D illustrate the development and removal of artifacts associated with the scanning technique of FIGURE 3;

FIGURE 4 illustrates a pulse inversion scanning technique of the present invention using multiline scanline reception;

FIGURE 5 illustrates in block diagram form the receiver of an ultrasonic diagnostic imaging system for processing signals in accordance with the inventive technique of FIGURES 1-3;

FIGURE 6 illustrates in block diagram form the receiver of an ultrasonic diagnostic imaging system which employs a [1 2 1] filter function;

FIGURE 7 illustrates in block diagram form the receiver of an ultrasonic diagnostic imaging system for producing both separated fundamental and harmonic signals which are blended into a common image;

FIGURE 8 illustrates in block diagram form the receiver of an ultrasonic diagnostic imaging system using multiline reception for producing pulse inversion separated harmonic signals in accordance with the principles of the present invention;

FIGURE 9 illustrates application of the principles of the present invention in single pulse imaging to reduce motion artifacts; and

FIGURE 10 illustrates in block diagram form an ultrasonic diagnostic imaging system which produces images with reduced motion artifacts in accordance with the inventive technique of FIGURE 9.

Referring first to FIGURE 1, a pulse inversion scanning technique of the present invention is shown. In FIGURES 1-4 and 9 the vectors of an image field (the region of the body which is being scanned) along which ultrasonic waves are transmitted and received are represented by arrows. These scanline arrows are shown in a relative spatial orientation in relation to the elements e of a linear array transducer 10 which transmits and receives the scanlines. The scanlines are depicted in a linear format, however they may also be transmitted and received in a sector or steered linear format as is known in the art. Scanline arrows pointing down in these drawings depict transmit scanlines and scanline arrows pointing up depict received scanlines. Straight lines depict image lines in their relative positions in an image.

In pulse inversion scanning in accordance with my aforementioned patent, two pulses of opposing phase or polarity are transmitted along each scanline direction, as represented by the paired transmit scanlines, the first pair of which is shown by transmit scanlines 1+ and 2-, with the "+" indicating a positive polarity transmit pulse and the "-" indicating a negative polarity transmit pulse. The relative phase opposition of the two transmit pulses or waveforms is preferably 180°; a lesser difference yields less than complete separation of linear and harmonic signal components when the resulting echoes are combined.

When pulse inversion is performed as shown in my patent, transmit scanlines 1+ and 2- yield received scanlines R_{1+} and R_{2-}, respectively, with the number indicating the corresponding transmit scanline. Transmit scanlines 3+ and 4- yield received scanlines R_{3+} and R_{4-}, and so forth along the array. Echoes along each received scanline are then summed or added on a common depth (z) basis to cancel fundamental signal components from tissue or contrast agents and leave only the harmonic signal components of the received echoes. Thus, the summation of received scanlines R_{1+} and R_{2-} produces an image line L1 of harmonic signals, the summation of received scanlines R_{3+} and R_{4-}, produces an image line L3 of harmonic signals, and so forth.

In accordance with the principles of the invention of the concurrently filed application, adjacent scanlines received from transmit scanlines of opposite polarity are summed to produce separated harmonic echo signals along image lines which are intermediate the adjacent scanlines. Received scanlines R_{2-} and R_{3+} are summed to produce harmonic echo signals along image line L2 which is intermediate image lines L1 and L3. Received scanlines

R_{4-} and R_{5+} are summed to produce harmonic echo signals along image line L4 which is intermediate image lines L3 and L5, and so on across the image field. It is seen that this further combination of adjacent scanlines produces a harmonic image with twice the line density of conventional pulse inversion imaging, using the same transmit pulse sequence as the conventional technique.

It will be appreciated that adjacent received scanlines R_{1+} and R_{4-} could also be used to separate the harmonic echoes of image line L2 since this pair of adjacent scanlines, like the R_{2-},R_{3+} pair, results from oppositely phased transmit pulses. However, since the R_{1+},R_{4-} pair is separated by the transmit- receive intervals of two other scanlines, 2- and 3+ and their received echoes, the R_{1+},R_{4-} pair is more susceptible to motion artifacts than is the time sequential R_{2-}, R_{3+} pair. Hence in the preferred embodiment time sequential adjacent scanlines are used to form the even-numbered intermediate image lines.

The received scanline processing arrangement of FIGURE 5 may be used to form the image lines shown in FIGURE 1. Echoes are received by the transducer array 10 following each transmit scanline and coherent echo signals are steered and focused by a receive beamformer 12 to produce a sequence of echo signals along the received scanline. Each received scanline is coupled to a line buffer 14 which delays each scanline by the time interval of a transmit-receive cycle such that the previous receive scanline and the current receive scanline are simultaneously applied to a summer 20. The summer 20 will therefore sum echoes of the two scanlines on a corresponding depth (z) basis, producing separated harmonic echo signals. When the sign of one of the signals being combined is changed by a sign change circuit 18, the arrangement of FIGURE 5 will produce separated linear signals, as indicated by the harmonic/linear control signal applied to the sign change circuit. An alternate way to achieve the same result is to replace the summer 20 with a difference circuit (subtractor). The separated harmonic or linear signals are then coupled to subsequent processing circuitry of the ultrasound system where the echo signals are detected, processed, and displayed in the usual manner.

Since the processing system of FIGURE 5 processes pairs of sequentially received scanlines, the summer 20 can produce the following combinations, depending upon the setting of the sign change circuit:

<u>Harmonic components:</u>

$L1=(R_{1+} + R_{2-})$; $L2=(R_{2-} + R_{3+})$; $L3=(R_{3+} + R_{4-})$;

$L4=(R_{4-} + R_{5+})$; . . .

Linear components:

$L1=(R_{1+} - R_{2-})$; $L2=(-R_{2-} + R_{3+})$; $L3=(R_{3+} - R_{4-})$;

$L4=(-R_{4-} + R_{5+})$; . . .

This operation is equivalent to convolving a spatial filter of the form [1 1] with the received data that is acquired by alternating the polarity (or phase) of the transmit pulse. Harmonic components and linear components are separated by inverting/noninverting the sign of the received data prior to the convolution.

In FIGURE 2 the lateral spacing of the transmitted and received scanlines is doubled in comparison with the FIGURE 1 embodiment. In the same manner as FIGURE 1, transmit scanlines 1+ and 2- yield received scanlines R_{1+} and R_{2-}, respectively, transmit scanlines 3+ and 4- yield received scanlines R_{3+} and R_{4-}, and so forth along the array 10, but at a two element spacing instead of a single element spacing. The received scanlines are processed by the processing system of FIGURE 5 in the same manner as before, producing image lines L1, L2, L3, L4,... of harmonic echo information but, due to the doubled scanline spacing, the image lines are of the same line density as the conventional pulse inversion technique. Compare the image line spacing of FIGURE 2 with the image line spacing of the odd-numbered image lines of FIGURE 1. But since scanlines are transmitted and received at twice the spacing as in FIGURE 1, only half as many transmit-receive intervals are required and the image lines for a full image frame at the conventional image line density are acquired in half the time. Thus, the frame rate of an image produced in accordance with the scanning sequence of FIGURE 2 is twice the conventional pulse inversion frame rate.

If the paired received scanlines (e.g., R_{1+},R_{2-} in FIGURE 2) are offset from each other rather than being co-aligned as shown in FIGURES 1 and 2, the combination of the two received scanlines will produce an image line of harmonic echoes at a line location intermediate that of the received scanlines.

The present inventors have found that the scanning techniques of FIGURES 1 and 2 can develop an artifact due to the line to line aperture variation. In FIGURE 2, for instance, it is seen that each pair of spatially aligned receive scanlines such as R_{1+} and R_{2-} are spatially aligned with each other and with their respective transmit scanlines. That is, both the transmit and receive apertures for the scanlines which are combined are commonly aligned and in spatial alignment with the resultant odd-numbered image line. But the even-numbered image lines are formed by combining scanlines from unaligned apertures. For example, received scanline R_{2-} and its transmit scanline are centered between the first and second

elements e of the array 10 while received scanline R_{3+} and its transmit scanline are centered between the third and fourth elements of the array. Thus, each image line across the image field is alternately formed from echoes from aligned and unaligned apertures. This alternation across the image can result in an annoying "picket fence" artifact in the image, particularly in the case of motion in the image field.

One approach to reducing this picket fence artifact is to filter, or average, consecutively received scanlines. Filtered image lines with reduced artifacts may be produced by convolving a filter of the form [1 2 1] with the received scanline data acquired from alternate polarity transmit pulses. As in the case of the arrangement of FIGURE 5, either harmonic or linear components may be separated by selectively inverting or noninverting the sign of the received data prior to convolution. The [1 2 1] filter will produce the following image lines:

Harmonic components:

$L1=(R_{1+} + 2R_{2-} + R_{3+})$; $L2=(R_{2-} + 2R_{3+} + R_{4-})$;

$L3=(R_{3+} + 2R_{4-} + R_{5+})$; $L4=(R_{4-} + 2R_{5+} + R_{6-})$; . . .

Linear components:

$L1=(R_{1+} - 2R_{2-} + R_{3+})$; $L2=(-R_{2-} + 2R_{3+} - R_{4-})$;

$L3=(R_{3+} - 2R_{4-} + R_{5+})$; $L4=(-R_{4-} + 2R_{5+} - R_{6-})$; . . .

Consistent with the principle of pulse inversion, it is seen that each of the separated components is composed of an equal contribution of echoes from both positive and negative (opposite polarity) transmit pulses. For instance, harmonic image line L1 is composed of two samples from positive transmit pulses (R_{1+} and R_{3+}) and two samples from negative transmit pulses ($2R_{2-}$).

An arrangement which implements the foregoing [1 2 1] filter is shown in FIGURE 6. This arrangement is similar to that of FIGURE 5, but includes a second line buffer 14' to twice-delay received scanlines and a second summer 20' which produces the $2R_{xx}$ term for the [1 2 1] filter function. In this embodiment the sign change circuit 18' functions by passing received data without alteration when harmonic components are being produced, and by changing the sign of alternate received scanlines when linear components are being produced. From the form of the linear components shown above, it is seen that the signs of the even-numbered received scanlines are inverted (R_{2-}, R_{4-}, etc.) and the signs of the odd-numbered received scanlines (R_{1+}, R_{3+}, R_{5+}) are unchanged. This operation of the sign

changing circuit of changing the sign of alternate lines is also effective for the embodiment of FIGURE 5.

Another scanning technique for high frame rate pulse inversion imaging is shown in FIGURE 3. In this embodiment each received scanline is received at an aperture offset from the transmit aperture by one element spacing. For instance, the echoes from transmit scanline 1+ are received at a received scanline R_{1+} aperture which is offset one element to the left of its transmit aperture, and the echoes from transmit scanline 2- are received at a received scanline R_{2-} aperture which is offset one element to the right of its transmit aperture. Likewise, the echoes from transmit scanline 3+ are received at a received scanline R_{3+} aperture which is offset one element to the left of its transmit aperture, and the echoes from transmit scanline 4- are received at a received scanline R_{4-} aperture which is offset one element to the right of its transmit aperture, and so on. When image line L1 is formed from received scanlines R_{1+} and R_{2-}, it is seen that the image line is in alignment with one aperture, the transmit aperture, but the other aperture, the receive aperture, is split on either side of the position of the image line. In like manner, while image line L2 is in alignment with one aperture, in this case the receive apertures of scanlines R_{2-} and R_{3+}, the transmit apertures of scanlines 2- and 3+ are split on either side of the position of the image line. Thus there is a common characteristic across the image field: each image line is in alignment with one aperture (transmit or receive) and unaligned with the other (which is split one element to either side of the image line.) While no image line is in complete alignment with both apertures, the uniformity of the aperture nonalignment across the image field will reduce the artifact resulting from the alternating aperture characteristics of FIGURES 1 and 2.

In digital ultrasound systems, received echoes are dynamically focused and temporally sampled. Such a sampled data system exhibits certain characteristics which require specific processing to avoid image artifacts. In particular, when the scanning technique of FIGURE 3 is implemented in a digital ultrasound system, interpolated samples on image lines aligned with the transmit aperture are misaligned row by row with interpolated samples on image lines aligned with the receive aperture.

FIGURES 3A-3C illustrate this problem. In FIGURE 3A, transmit apertures TL and TR are aligned with an image line LT. The respective receive apertures OL and OR are located to the left and to the right of the transmit apertures. Echo data samples RL_x and RR_x are received from apertures OL and OR at uniformly spaced distances (or uniformly spaced times) x in the image field. When these data samples RL_x and RR_x are combined to interpolate image line samples at the desired intermediate locations 60, 62, 64 in line with the

transmit aperture, the resultant interpolated samples are not uniformly spaced but are located on the intersections of the isochrons 66 of the respective receive apertures as shown by interpolated samples 61, 63, and 65.

FIGURE 3B illustrates the spacing of the samples when the interpolated image line is aligned with the receive apertures. The transmit apertures TL and TR are located to the left and right of the aligned receive apertures OL and OR. Echo data samples RL_x and RR_x, being received from aligned received apertures OL and OR, will result in uniformly spaced image line samples 70, 72, 74. This drawing shows that interpolated samples from aligned receive apertures will remain uniformly spaced.

When the interpolated samples of FIGURES 3A and 3B are combined in an image field, it is seen that the spacing of the image line samples varies from one image line to the next across the image field, as shown by FIGURE 3C. Image line samples aligned with the transmit apertures exhibit one spacing, and image line samples aligned with the receive apertures exhibit another spacing. These unregistered image samples will result in a "shimmering" artifact, particularly in the near field of the resultant image where the misregistration is the most severe.

One way to remedy this shimmering artifact problem is to employ a signal resampling process. Axial resampling can recalculate sample values at the desired locations along the image line using the values of the acquired, misregistered samples of the image line. The resampling process can create its own artifact if only the misregistered image lines are resampled, for this will alter the bandwidth from line to line. Such artifacts can be reduced by employing a double resampling process on all image lines, computing intermediate values first, and then final values at the desired sample locations on the lines, or by resampling all image lines to a sample alignment different from that of both types of received sample alignments. Since the pulse inversion process is a linear operation, the resampling process can be implemented before or after harmonic/linear separation.

The shimmering artifact can also be eliminated by processing the received scanlines using a spatial filter. Previous examples have demonstrated the use of [1 1] and [1 2 1] filters. In the case of the [1 2 1] filter it is seen that

$$R_{1+} + 2R_{2-} + R_{3+} = (R_{1+} + R_{2-}) + (R_{2-} + R_{3+})$$

This shows that the effect of applying a [1 2 1] filter is equivalent to averaging the transmit aligned pixel with the receive aligned pixel to reduce the image artifact. But the [1 2 1] filter will only reduce, not eliminate, the artifact since the transmit and receive pixel apertures are not perfectly aligned.

A higher order [1 3 3 1] filter will effectively eliminate the artifact, however, as illustrated by FIGURE 3D. In this drawing the samples 70-79 show the alternate alignment of image line pixel data as a result of [1 1] filtering, as in FIGURE 3C. The odd-numbered image lines are aligned with the transmit scanlines and the even-numbered image lines are aligned with the received scanlines and the scanlines are equally laterally spaced as a result of the scanning format of FIGURE 3. To register this image data laterally, each pair of consecutive transmit-aligned scanlines is interpolated to produce intermediate pixel data aligned with the receive-aligned scanlines, and each pair of consecutive receive-aligned scanlines is interpolated to produce intermediate pixel data aligned with the transmit-aligned scanlines. This intermediate pixel data is then averaged with the axially adjacent sample data to produce the desired image data.

As an example, the data on lines L1, L2 and L3 is initially of the form:

L1: $(R_{1+} + R_{2-})$ L2: $(R_{2-} + R_{3+})$ L3: $(R_{3+} + R_{4-})$

From the two adjacent scanlines aligned with the transmit beams, L1 and L3, intermediate interpolated scanline data 80,81 is produced:

(L1+L3)/2: $0.5((R_{1+} + R_{2-})+(R_{3+} + R_{4-}))$

This intermediate interpolated data is axially interpolated with the uninterpolated data on the receive aligned scanline L2 to produce the desired aligned interpolated pixels 90,91:

(L1+L3)/4 + L2/2 = L1/4+L3/4+L2/2: $0.25(R_{1+} + 3R_{2-} + 3R_{3+} + R_{4-})$

In the same manner, intermediate interpolated scanline data 82,83 is produced from adjacent scanlines aligned with the received scanlines:

(L2+L4)/2: $0.5((R_{2-} + R_{3+})+(R_{4-} + R_{5+}))$

This intermediate interpolated data is axially interpolated with the uninterpolated data on the transmit aligned scanline L3 to produce desired aligned interpolated pixels 92,93:

(L2+L4)/4 + L3/2 = L2/4+L4/4+L3/2: $0.25(R_{2-} + 3R_{3+} + 3R_{4-} + R_{5+})$

Neglecting the scaling factor of 0.25, the aligned pixels are of the form

L2: $R_{1+} + 3R_{2-} + 3R_{3+} + R_{4-}$ L3: $R_{2-} + 3R_{3+} + 3R_{4-} + R_5$

This is effectively equivalent to processing the scanline data with a [1 3 3 1] filter. The preceding example describes the processing to separate harmonic image line data. Linear image line data can be obtained by inverting the sign of the received data acquired in response to the transmit pulses of inverted (negative) sign or polarity. The separated linear components will thus be of the form

L2: $R_{1+} - 3R_{2-} + 3R_{3+} - R_{4-}$ L3: $-R_{2-} + 3R_{3+} - 3R_{4-} + R_5$

Use of this processing technique can eliminate the shimmering artifact as a result of realignment of the image pixels from image line to image line. Although the image pixels are not sampled perfectly uniformly in theory, the sampling error is negligibly small when the image lines are processed with a [1 3 3 1] or higher order filter.

FIGURE 7 illustrates a processing system which simultaneously separates both linear and harmonic echo signal components, then blends them together in a single image as a function of depth. Such a blended image can take advantage of the low nearfield clutter performance which is possible with harmonic components, and the better depth penetration of linear components. In FIGURE 7 the summer 20 additively combines sequential scanlines received from oppositely phased transmit signals to produce separated harmonic signal components as in the case of the embodiment of FIGURE 5. A subtractor 24 takes the difference of sequential scanlines received from oppositely phased transmit signals to produce separated linear (fundamental) signals. The signals from the summer 20 and subtractor 24 can if desired be separately processed and displayed as separate or overlaid harmonic and fundamental images. In this embodiment the respective harmonic and fundamental signals are multiplied by weighting functions by multipliers 22 and 26. The harmonic signal components are weighted by a depth-variable weighting factor $k_H(z)$. The linear signal components are also weighted by a depth-variable weighting factor $k_f(z)$. In a preferred embodiment the weighting factors vary in an inverse relationship, with harmonic components more heavily weighted in the near field and linear components more heavily weighted in the far field. The weighted signal components are combined by a summer 30, then forwarded for detection, image processing, and display.

It will be appreciated that other factors can be used to control the variability of the weighting factors such as other spatial dimensions or time. Variable blending can take advantage of the different characteristics of linear and harmonic signals in different imaging applications.

A multiline technique producing an even greater frame rate of display is shown in FIGURE 4. In this embodiment only a single transmit scanline is produced at a two element spacing. The polarity or phasing of the transmit pulses alternates from one transmit scanline to the next. The acoustic field of each transmitted scanline is broad enough to encompass two receive scanlines which are simultaneously received, as shown in U.S. Pat. 4,644,795. Thus, "multiline" reception is employed for multiple scanlines following each transmit wave. In the illustrated embodiment transmit scanline 1+ results in the reception of a receive scanline to the right and left of the center of the transmit aperture, R_{1L+} and R_{1R+}.

Similarly, transmit scanline 2- results in the reception of receive scanlines R_{2L-} and R_{2R-}, and transmit scanline 3+ results in the reception of receive scanlines R_{3L+} and R_{3R+}, and so on. In this embodiment the received scanlines are spaced one element to the left and right of the transmit scanline so that successive received scanlines are in alignment, however, this is not required; the technique is applicable even when the received scanlines do not overlap, although care must be taken to avoid artifacts from spatial aliasing when greater scanline spacing is employed.

Successively received scanlines are then combined to produce separated harmonic (or linear) signals along the image lines depicted at the bottom of FIGURE 4. Image line L1 is formed by combining received scanlines R_{1L+} and R_{2L-}, which are derived from oppositely phased transmit signals. Image line L2 is formed by combining received scanlines R_{1R+} and R_{2L-}, which are likewise derived from oppositely phased transmit signals. Image line L3 can be formed by combining R_{1R+} and R_{2R-}, or by combining R_{2L-} and R_{3L+}. Like the embodiment of FIGURE 3, each image line is aligned with one of the transmit or receive apertures, and unaligned with respect to the other, which is split on either side of the image line. These image lines are subject to the same artifacts as the FIGURE 3 technique, and thus benefit from higher order filtering. Using the [1 3 3 1] filter, image line L2 is formed by combining received scanlines $R_{1L+} + 3R_{1R+} + 3R_{2L-} + R_{2R-}$ which are derived from consecutive, oppositely phased transmit signals. Image line L3 is formed by combining received scanlines $R_{1R+} + 3R_{2L-} + 3R_{2R-} + R_{3L+}$, which are likewise derived from consecutive, oppositely phased transmit signals. Image line L4 can be formed by combining $R_{2L-} + 3R_{2R-} + 3R_{3L+} + R_{3R+}$. Like the embodiment of FIGURE 3, each image line is aligned with one of the transmit or receive apertures, and unaligned with respect to the other, which is split on either side of the image line. Thus, this filtering technique has the same beneficial artifact performance as in the embodiment of FIGURE 3.

An ultrasound receive signal processor for performing the scanning technique of FIGURE 4 is shown in FIGURE 8. In this system the elements of the transducer array 10 are coupled to individual channels of a transmitter 16, which provide individually timed transmit signals to each element to steer and focus the transmit scanline beam as desired. The transducer elements are also coupled in parallel to the inputs of two receive beamformers, beamformer 12L and beamformer 12R, preferably by multiplexing which enables the inputs to the beamformers to be changed so that they may be operated as two multiline beamformers or as one single-line beamformer. The received scanlines produced by the two beamformers are coupled to the inputs of line buffers 14 and to the inputs of summers 42, 44, and 46. The

summers combine sequential scanlines from opposite polarity transmit pulses and produce image lines of separated harmonic echo components. Separated linear signal components can be obtained by the use of sign change circuits at the output of each beamformer (not shown) to change the sign of signals received from alternate transmit pulses. A filter and line sequencer 50 receives image line data from the three summers, buffers the data as required, and transmits image line data to the detection, processing and display circuitry of the ultrasound system in a desired image line sequence. Alternatively, the filter and line sequencer can comprise a multiple entry frame store which stores multiple selected image lines for subsequent processing and display.

In operation, beamformer 12L will sequentially produce scanlines R_{1L+}, R_{2L-}, R_{3L+}, R_{4L-}, and so on in response to the transmit scanline sequence of FIGURE 4. The beamformer 12R will concurrently produce scanlines R_{1R+}, R_{2R-}, R_{3R+}, R_{4R-}, and so on. These sequences result in the production of the following combinations at the outputs of the summers:

$$(R_{1L+} + R_{2L-})\ (R_{2L-} + R_{1R+})\ (R_{1R+} + R_{2R-})\ (R_{2R-} + R_{3L+})$$
$$(R_{3L+} + R_{4L-})\ (R_{4L-} + R_{3R+})\ (R_{3R+} + R_{4R-}) \ldots$$

where this sequence of image lines is produced by summer 42, summer 44, summer 46, summer 44, summer 42, summer 44, summer 46, and so on. Sequencing the summer outputs in this order will produce the image line sequence L1, L2, L3, L4, L5, and so on as shown at the bottom of FIGURE 4.

Since the scanning technique of FIGURE 4 will benefit by the same filtering techniques as the previous embodiment, in a preferred embodiment of FIGURE 8, the filter and line sequencer 50 processes the scanline data with a [1 3 3 1] filter in the same manner as the previous embodiment. This will lead to the production of harmonic signal components of the form:

L2: $(R_{1L+} + 3R_{1R+} + 3R_{2L-} + R_{2R-})$
L3: $(R_{1R+} + 3R_{2L-} + 3R_{2R-} + R_{3L+})$
L4: $(R_{2L-} + 3R_{2R-} + 3R_{3L+} + R_{3R+})$
L5: $(R_{2R-} + 3R_{3L+} + 3R_{3R+} + R_{4L-})$
L6: $(R_{3L+} + 3R_{3R+} + 3R_{4L-} + R_{4R-})$

By inverting the sign of the received data acquired in response to the transmit pulses of inverted (negative) sign or polarity, the [1 3 3 1] filter will produce linear signal components of the form:

L2: $(R_{1L+} + 3R_{1R+} - 3R_{2L-} - R_{2R-})$
L3: $(R_{1R+} - 3R_{2L-} - 3R_{2R-} + R_{3L+})$
L4: $(-R_{2L-} - 3R_{2R-} + 3R_{3L+} + R_{3R+})$
L5: $(-R_{2R-} + 3R_{3L+} + 3R_{3R+} - R_{4L-})$
L6: $(R_{3L+} + 3R_{3R+} - 3R_{4L-} - R_{4R-})$

In accordance with the principles of the present invention, the scanning technique of FIGURE 4 is applied to the interpolation of multiline received signals to cure a defect of prior art arrangements. The simplest conventional multiline sequence is to receive two scanlines for every transmit pulse, one scanline on either side of the center of the transmit beam. One prior art interpolation technique forms one image line by averaging the two received scanlines, and another image line by averaging adjacent scanlines from two consecutive transmit pulses, that is, the scanline to the left of one transmit beam is averaged with the scanline to the right of the neighboring transmit beam. Received scanlines across the image field are averaged in this manner to develop an image of interpolated scanlines. This interpolation technique is susceptible to an alternating motion artifact similar to that described above, because the first pair of scanlines (and every odd-numbered pair) which are averaged are concurrently received and the second pair of scanlines (and every even-numbered pair) which are averaged are sequentially received. If there is motion in the image field, the concurrently received scanlines will be equally affected because they are produced by a single transmit pulse. The sequentially received scanlines will be differently affected by motion because they are developed by temporally different transmit pulses and each scanline will reflect the position of moving materials as of the moment they are produced. Thus, odd-numbered lines will not have a motion artifact and even-numbered lines will, creating a scintillation-type artifact when there is motion in the image plane.

In accordance with the principles of the present invention, this motion artifact of multiline interpolation is avoided as shown in FIGURE 9. In this drawing a sequence of transmit pulses T_1, T_3, T_5,... is transmitted across the image field. A pair of scanlines are received in response to each transmit pulse. For instance, scanlines R_{10} and R_{12} are received in response to transmit pulse T_1, where the first subscript refers to the number of the transmit

pulse which produced the scanline, and the second subscript refers to the relative position of the received scanline across the image field. The second transmit pulse T_3 results in the reception of scanlines R_{32} and R_{34}, and so on.

The prior art technique for forming interpolated image lines from these scanlines is to average R_{10} and R_{12} to form image line L1; R_{12} and R_{32} to form image line L2; and so on across the image field. But L1 is formed from temporally identical received scanlines and L2 is formed from temporally different received scanlines, giving rise to the motion artifact. The technique of the present invention overcomes this problem by consistently forming image lines from temporally different received scanlines. That is, L1 is formed by interpolating scanlines R_{10} and R_{32}, image line L2 is formed by interpolating scanlines R_{12} and R_{32}, image line L3 is formed by interpolating scanlines R_{32} and R_{54}, and so on as shown by the ovals 1, 2 and 3 encompassing these scanline designators in FIGURE 9. This results in a uniform characteristic of the interpolated image lines across the image field, since each image line is formed from two temporally different scanlines. This method of interpolation is continued across the image field as the encompassing ovals 4, 5, and 6 in FIGURE 9 indicate.

The present inventors have noted that, while the above two-line interpolation technique reduces the motion scintillation artifact, an error is introduced by the variation in the locations of the transmit and receive apertures from line to line across the image field. Hence, the present inventors prefer the use of a three-line lateral filter of the form $(R_x + 2R_y + R_z)$ for use as the line interpolator for FIGURE 9. This set of filter coefficients advantageously weights two scanlines acquired on one side of a transmit beam with a double-weighting of a scanline acquired on the other side. This filter will form an image line L1.5 by interpolating scanlines R_{10}, $2R_{12}$ and R_{32}; image line L2.5 is formed by interpolating scanlines R_{12}, $2R_{32}$, and R_{34}; image line L3.5 is formed by interpolating scanlines R_{32}, $2R_{34}$ and R_{54}, and so on. Each of these interpolated lines is intermediate the integer lines shown in FIGURE 9. This filter form is also effective for performing high frame rate pulse inversion harmonic separation. Referring to FIGURE 4, for instance, it may be seen that a lateral filter of this form will sequentially produce

$$(R_{1L+} + 2R_{2L-} + R_{1R+}) \quad (R_{2L-} + 2R_{1R+} + R_{2R-}) \quad (R_{1R+} + 2R_{2R-} + R_{3L+})$$

This sequence is seen to combine two weights of scanlines received from positive (or negative) polarity transmit pulses with two weights of scanlines received from negative (or positive) polarity transmit pulses, thereby providing complete harmonic separation.

The image line interpolation technique of FIGURE 9 can be carried out by the multiline receiver and interpolation arrangement of FIGURE 10. In this system the elements e of the array transducer 10 are individually driven by a transmitter 136 to steer a focused transmit beam from the desired point along the transducer array in the desired direction in the image field. Conductors or, preferably, multiplexers couple echo signals received by the elements e to a multiline beamformer 132,134, as indicated by the arrow 130. The multiline beamformer 132,134 may be two separate beamformers, or separately controllable and separately summing partitions of a single beamformer. Each multiline beamformer partition produces a received scanline, one to the left and one to the right of the transmit beam transmitted under control of transmitter 136. Each pair of concurrently received scanlines is stored temporarily in a line memory 138 which acts as a buffer, and forwarded at the appropriate time with subsequently received scanlines to line interpolator 140. The line interpolator forms an image line by interpolating pairs of scanlines as shown in FIGURE 9, or preferably implements a three-line lateral filter of the form ($R_x + 2R_y + R_z$). The interpolated image lines are coupled to detection and signal processing circuitry 142 and a scan converter 146 for processing and display of an image on a display 150. It is seen that the apparatus of FIGURE 10 when operated in accordance with the technique of FIGURE 9 can form high frame rate interpolated multiline images of virtually every sort of echo signal. This apparatus and technique will find use in B mode, Doppler and harmonic imaging.

CLAIMS:

1. A method for producing an ultrasonic image of interpolated image lines with reduced susceptance to motion artifacts comprising the steps of:

transmitting a plurality of laterally spaced ultrasonic beams in an image field;

receiving a plurality of laterally spaced receive beams in response to each transmitted beam; and

producing interpolated image lines from said receive beams, successive ones of which are an interpolation of receive beams produced in response to multiple transmitted beams; and

detecting and displaying said interpolated image lines.

2. The method of Claim 1, wherein the step of transmitting transmits a sequence of laterally spaced beams of the form T_1, T_3, T_5, T_7.

3. The method of Claim 2, wherein the step of receiving receives pairs of scanlines of the form (R_{10},R_{12}), (R_{32},R_{34}), (R_{54},R_{56}), (R_{76},R_{78}).

4. The method of Claim 3, wherein the step of producing interpolated image lines produces lines of the form $(R_{10} + R_{32})$, $(R_{12} + R_{32})$, $(R_{32} + R_{54})$, $(R_{34} + R_{54})$.

5. The method of Claim 3, wherein the step of producing interpolated image lines comprises the step of laterally filtering two or more adjacent received scanlines.

6. The method of Claim 5, wherein the step of laterally filtering comprises using a filter function of the form [1 2 1] to produce image lines of the form $(R_x + 2R_y + R_z)$.

7. The method of Claim 6, wherein the step of laterally filtering produces image lines of the form $(R_{10} + 2R_{12} + R_{32})$, $(R_{12} + 2R_{32} + R_{34})$, $(R_{32} + 2R_{34} + R_{54})$.

8. An ultrasonic diagnostic imaging system which produces an ultrasonic image of interpolated image lines with reduced susceptance to motion artifacts comprising:

an array transducer;

a beamformer, coupled to said array transducer, which controls said array transducer to transmit a sequence of laterally spaced ultrasonic beams in an image field, and which forms multiple laterally spaced scanlines in response to each transmitted beam; and

an interpolator, coupled to said beamformer and responsive to said scanlines, which produces interpolated image lines, successive ones of which are an interpolation of scanlines produced in response to multiple transmitted beams; and

an image processor which detects and displays said interpolated image lines.

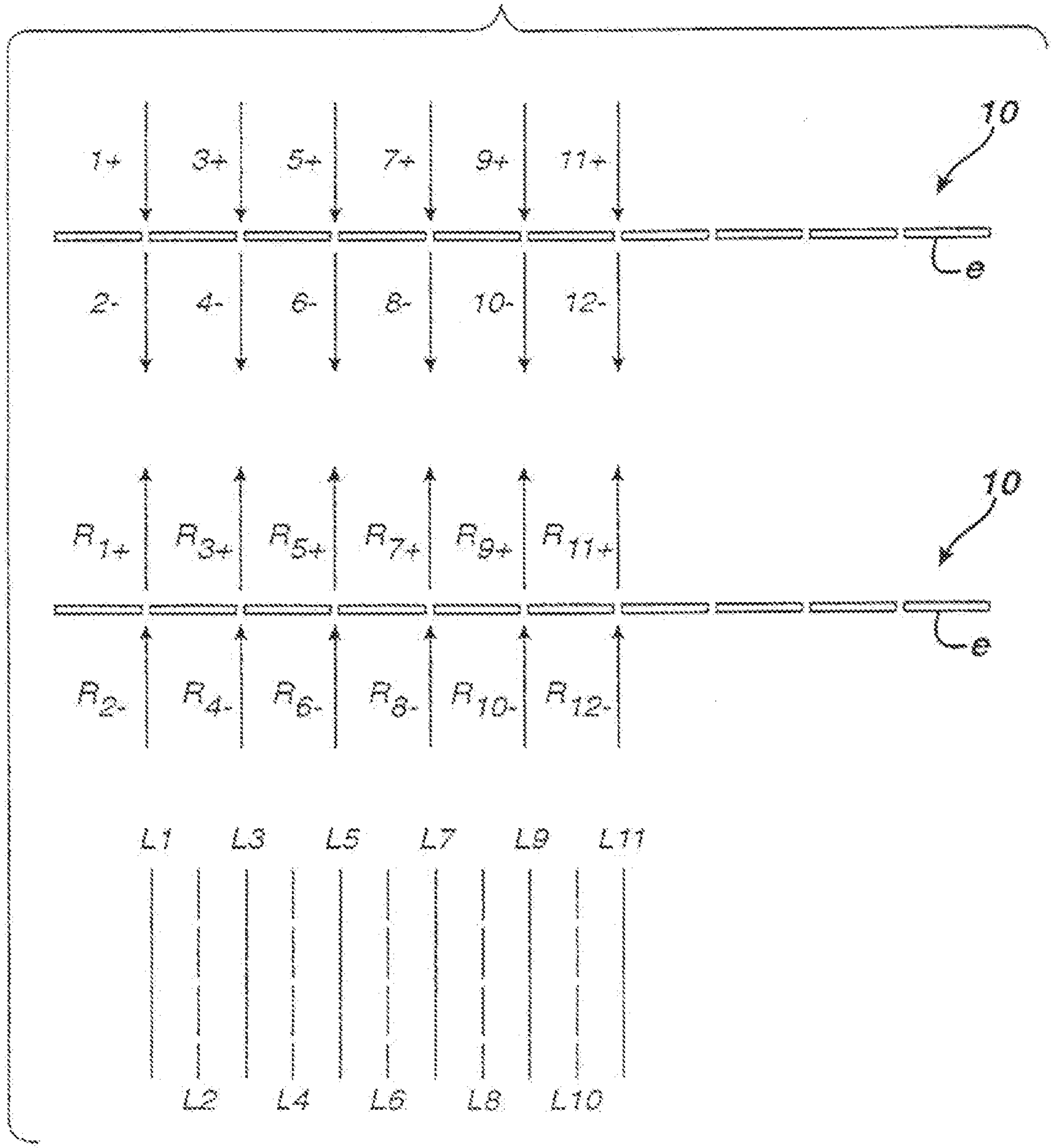
9. The ultrasonic diagnostic imaging system of Claim 8, wherein said beamformer includes a receive beamformer which forms two scanlines in response to each transmitted beam on opposite sides of said transmitted beam.

10. The ultrasonic diagnostic imaging system of Claim 9, wherein said interpolator comprises a lateral filter.

11. The ultrasonic diagnostic imaging system of Claim 10, wherein said lateral filter performs a filter function of the form $(R_x + R_y)/2$ to produce successive image lines, wherein R_x and R_y are scanlines produced by said receive beamformer in response to different transmitted beams.

12. The ultrasonic diagnostic imaging system of Claim 10, wherein said lateral filter is a [1 2 1] filter which performs a filter function of the form $(R_x + 2R_y + R_z)$ to produce successive image lines, wherein two of R_x, R_y and R_z are scanlines produced by said receive beamformer in response to different transmitted beams.

FIG. 1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5+
7+
9+
11+
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2-
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R_{5+}
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R_{9+}
R_{11+}
e
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L6
L8
L10

FIG. 2

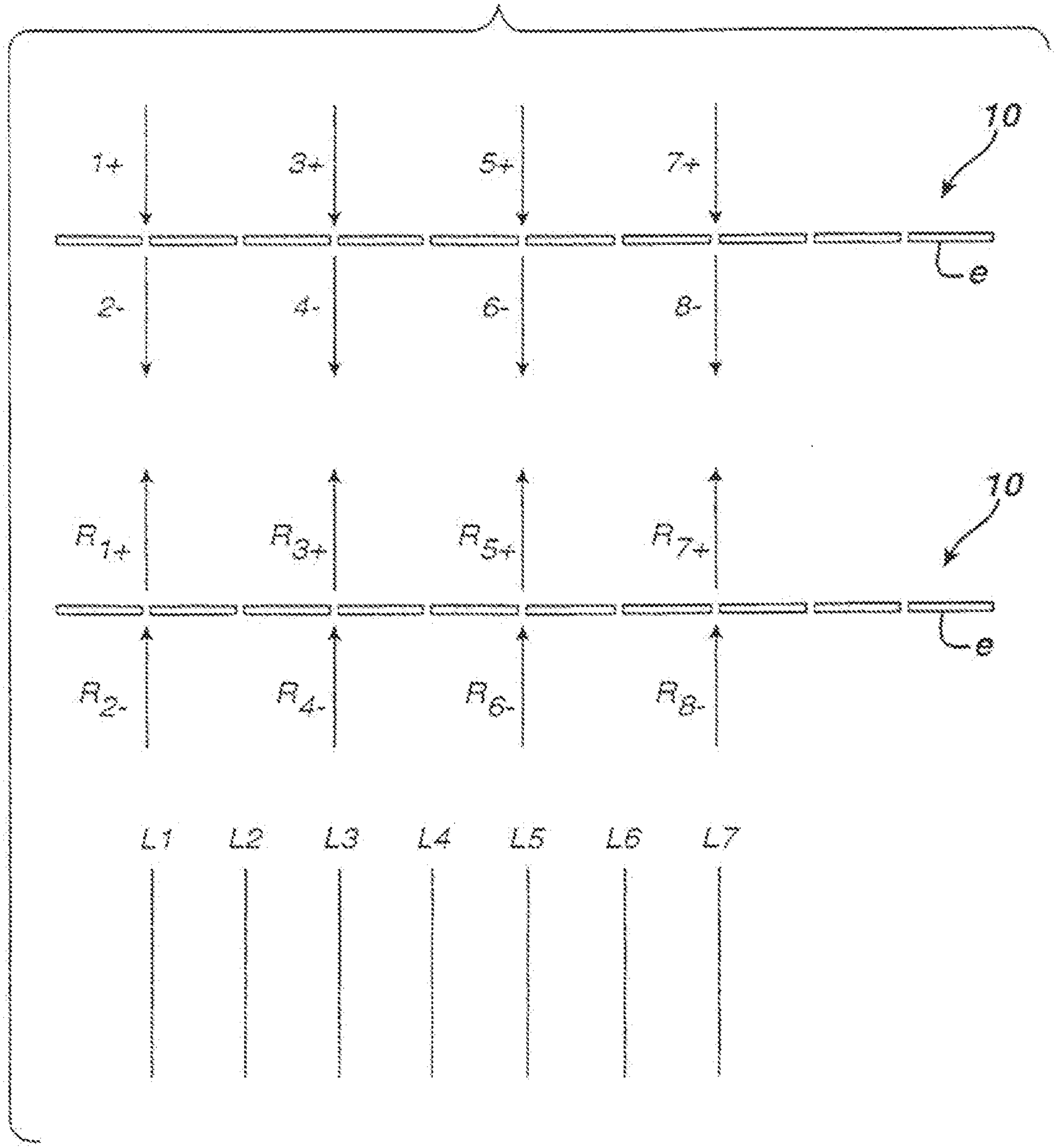


FIG. 3

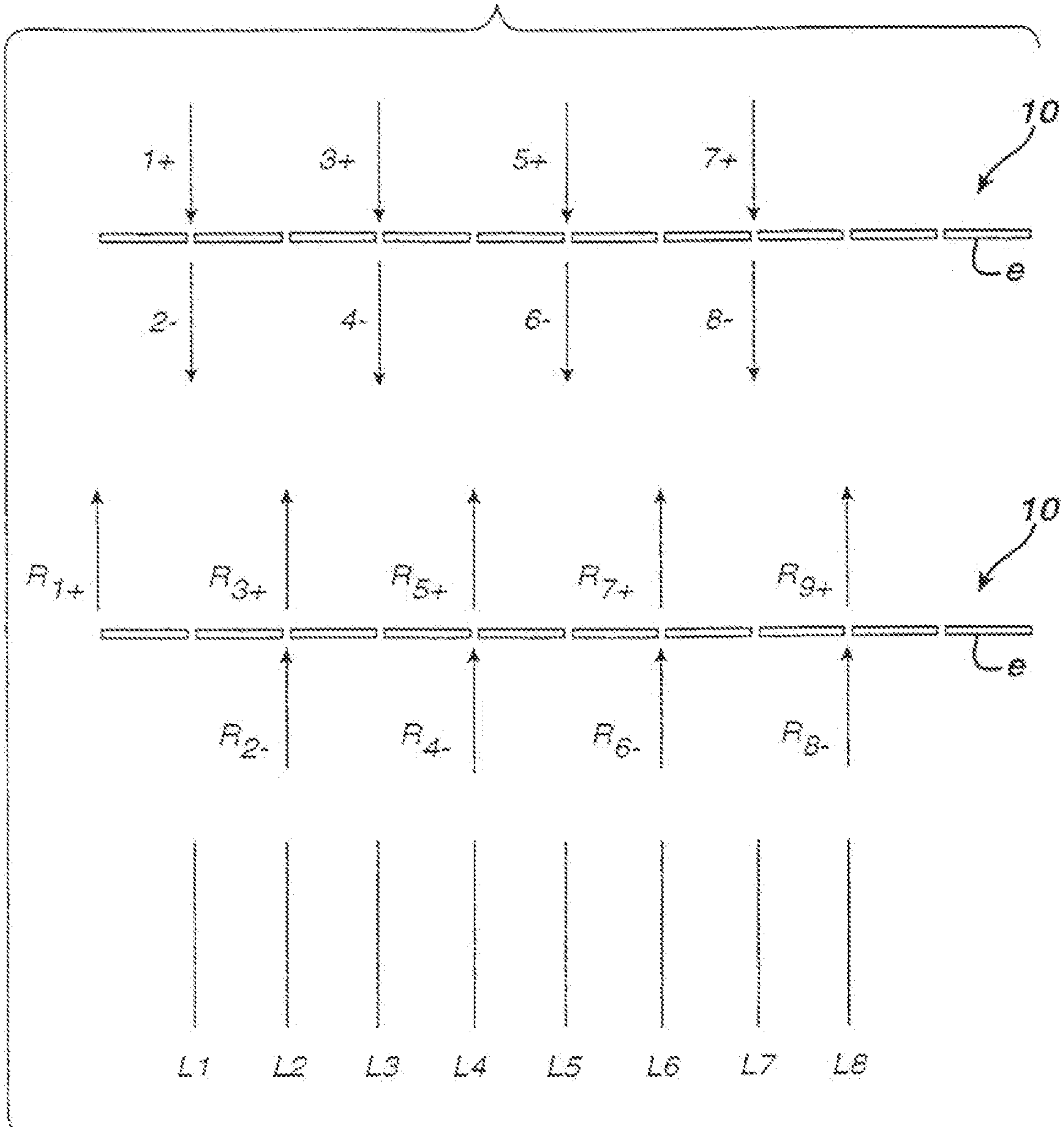
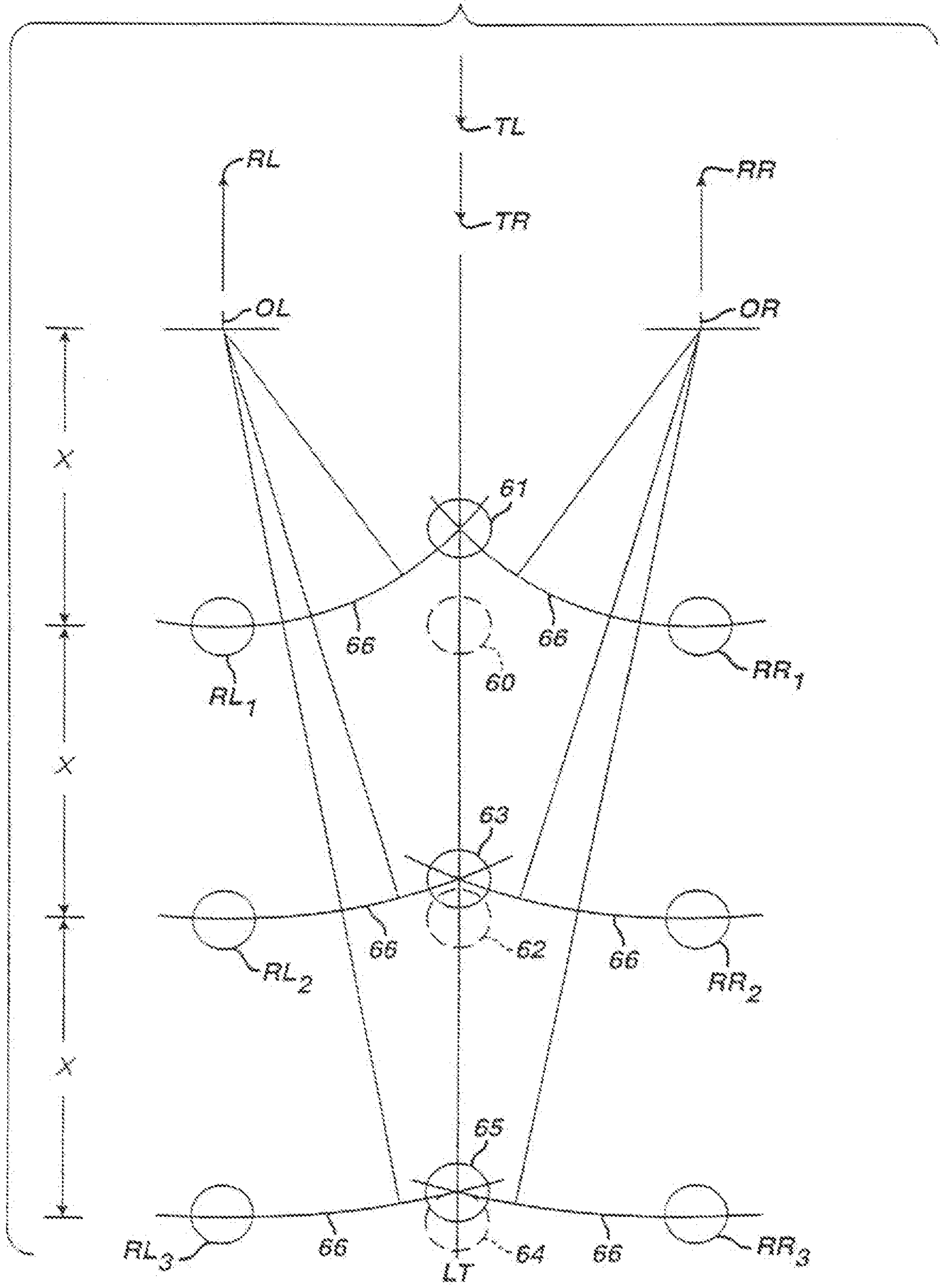


FIG. 3A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TR
RL
RR
OL
OR
X
X
X
61
60
63
62
65
64
66
66
66
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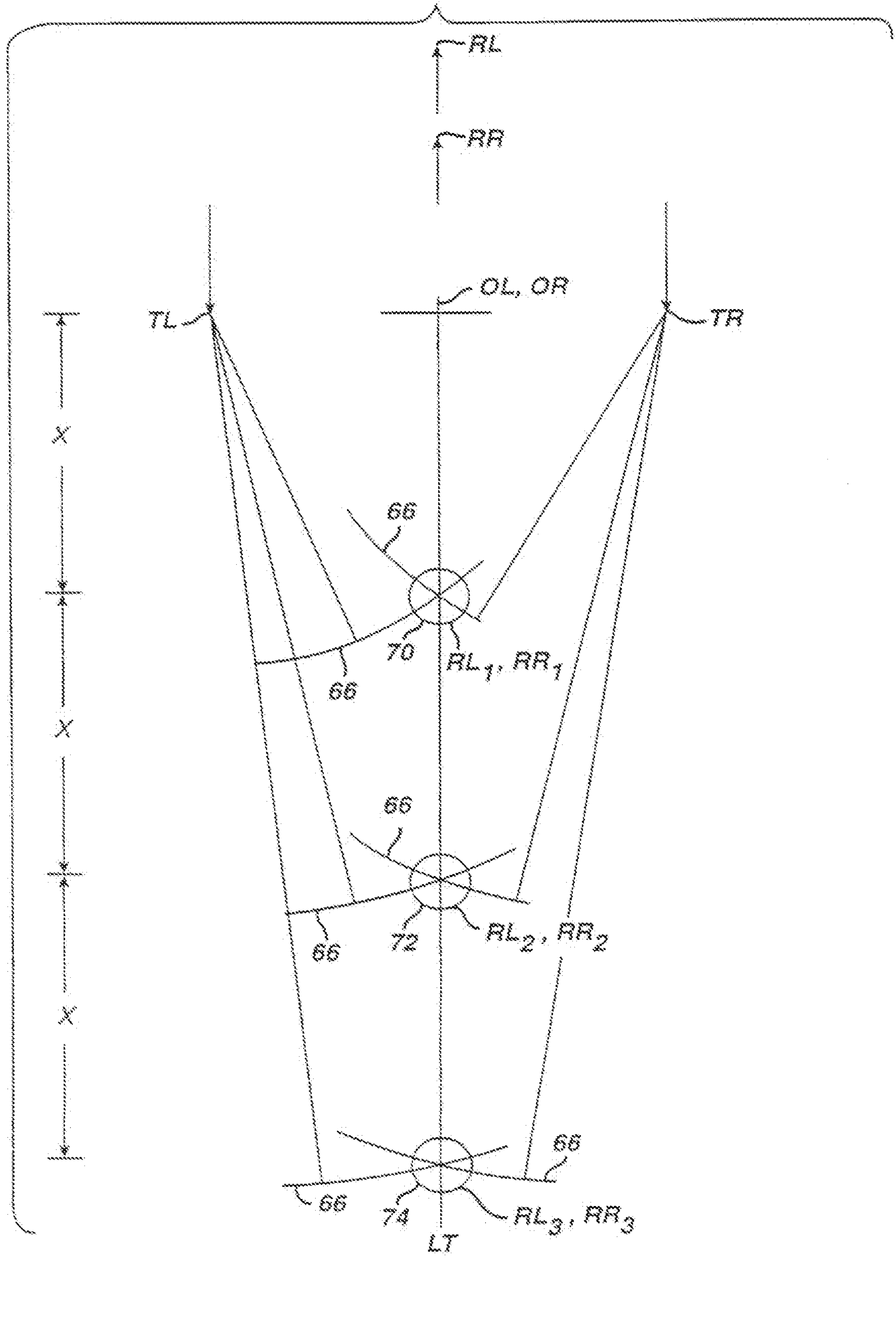
66
RL1
RR1
RL2
RR2
RL3
RR3
LT

5/14

FIG. 3B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X
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66
74
RL_3, RR_3
LT

FIG. 3C

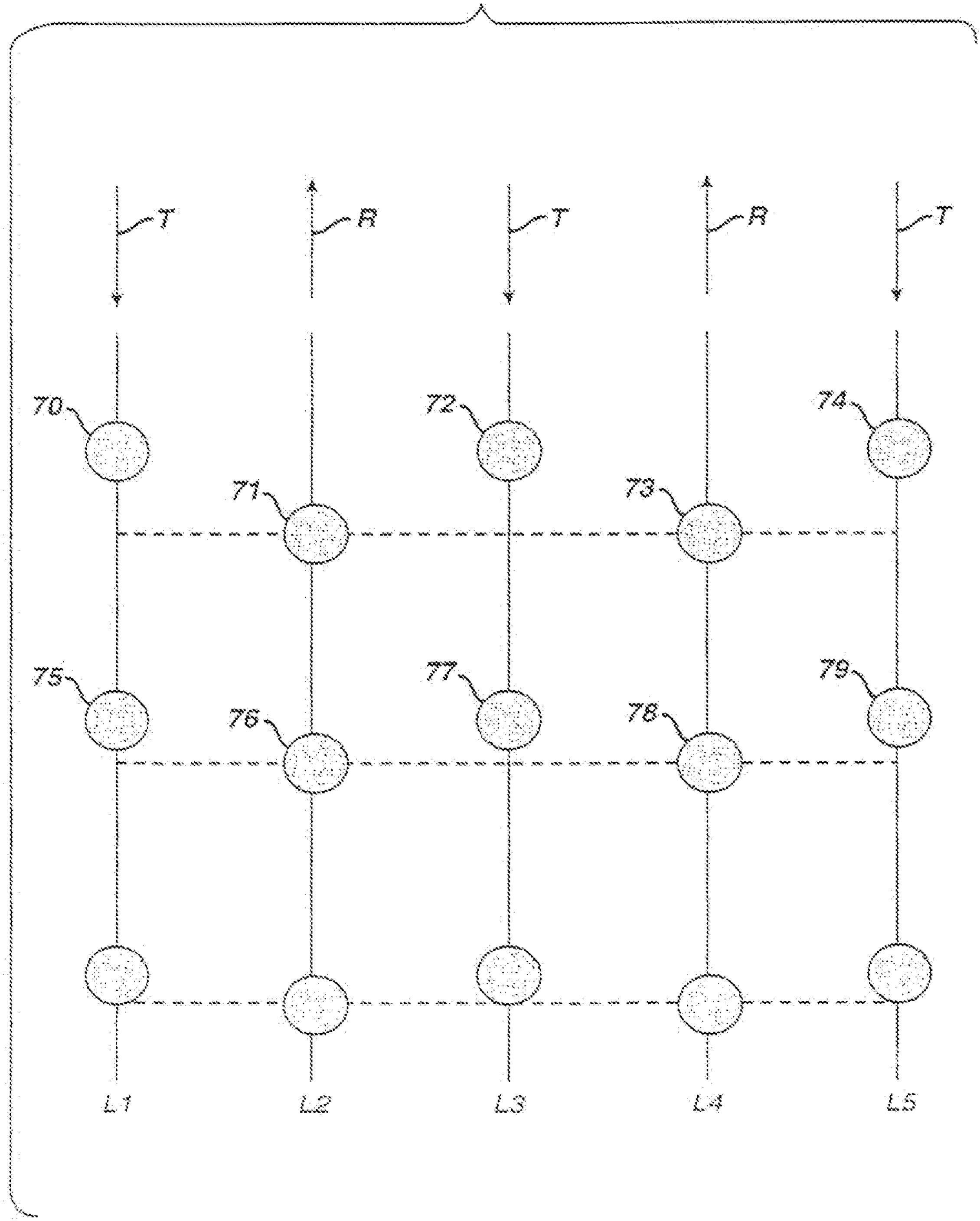
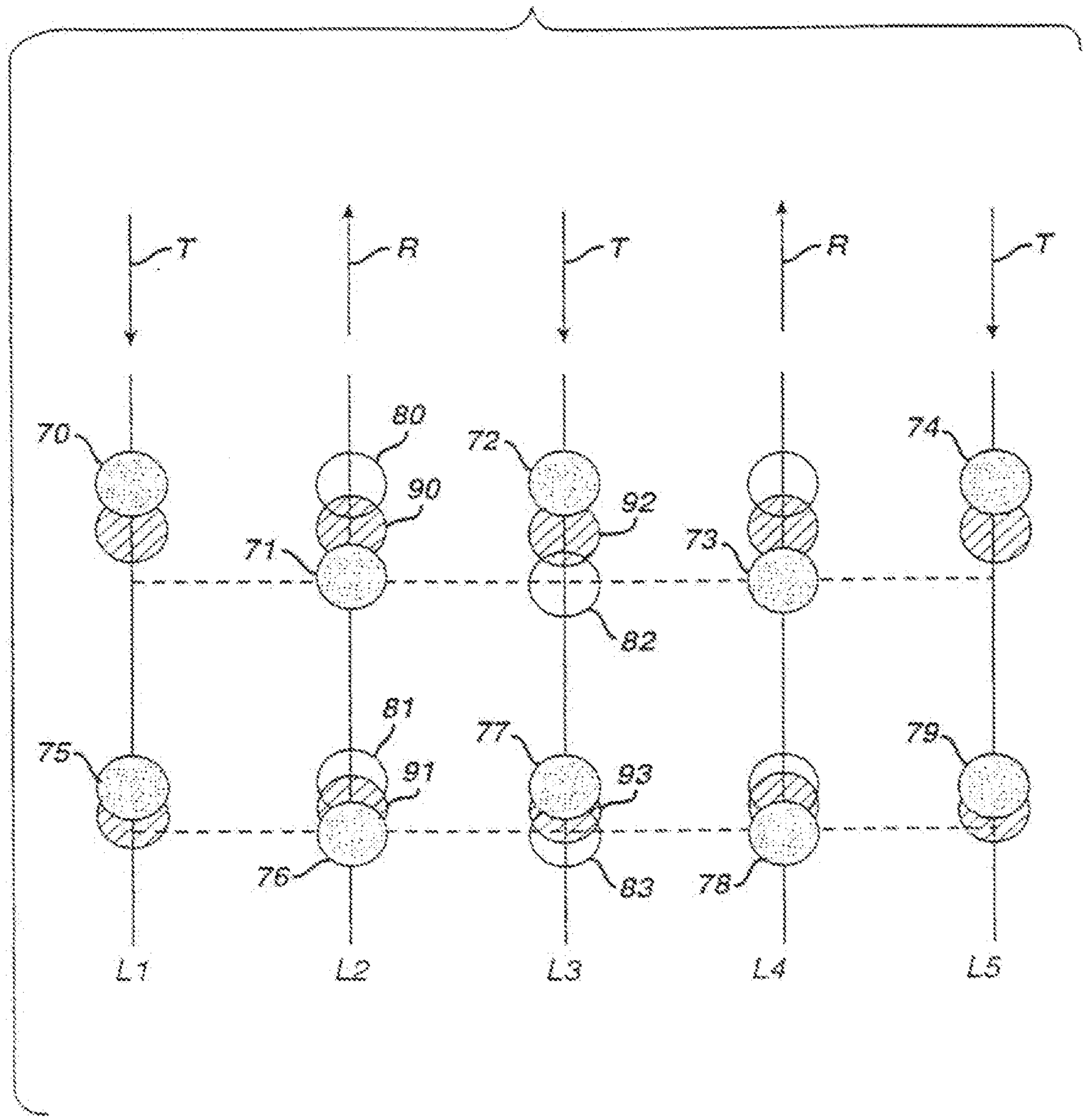


FIG. 3D


T
R
T
R
T
70
80
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74
90
92
71
73
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81
77
79
75
91
93
76
83
78
L1
L2
L3
L4
L5

FIG. 4

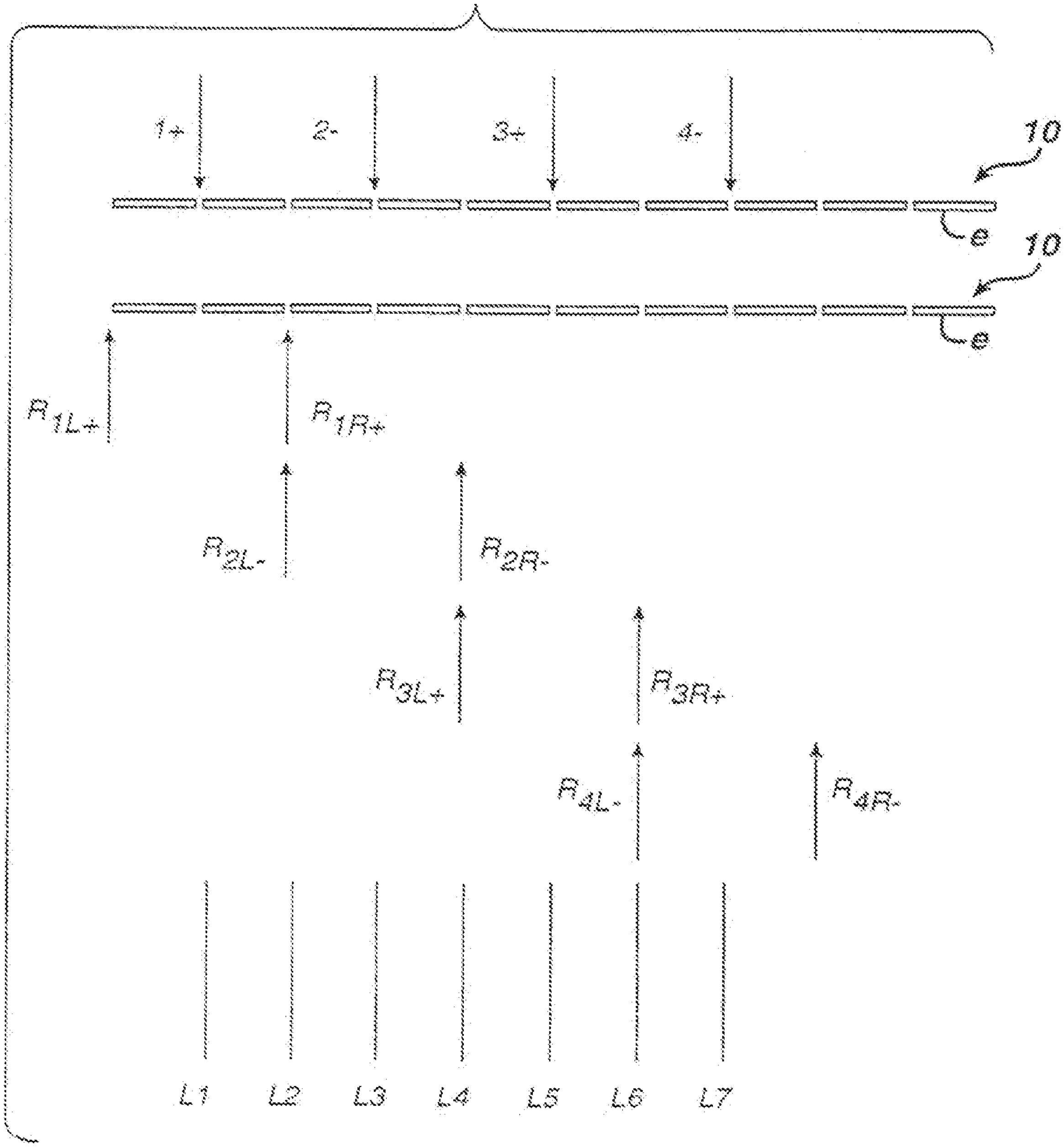
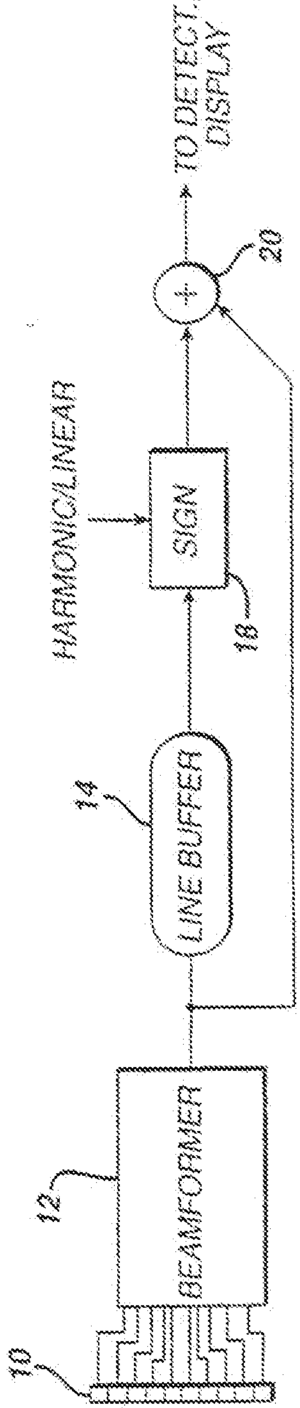


FIG. 5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12
BEAMFORMER
14
LINE BUFFER
HARMONIC/LINEAR
SIGN
18
+
20
TO DETECT.,
DISPLAY

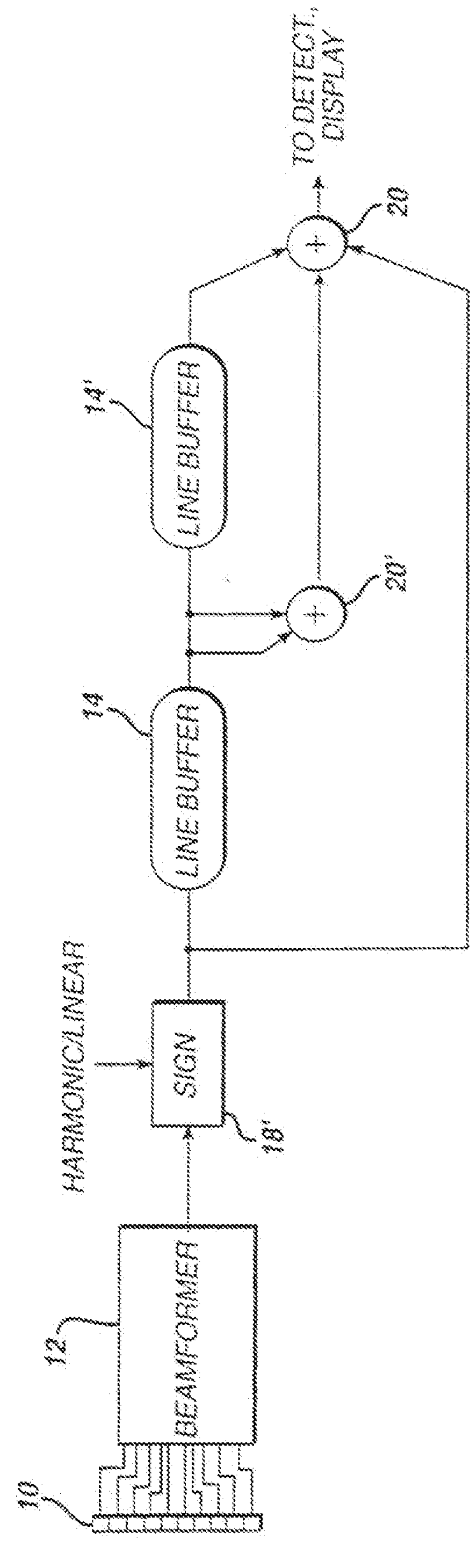

TO DETECT., DISPLAY
20
14'
LINE BUFFER
20'
14
LINE BUFFER
HARMONIC/LINEAR
SIGN
18'
12
BEAMFORMER
10

FIG. 6

FIG. 7

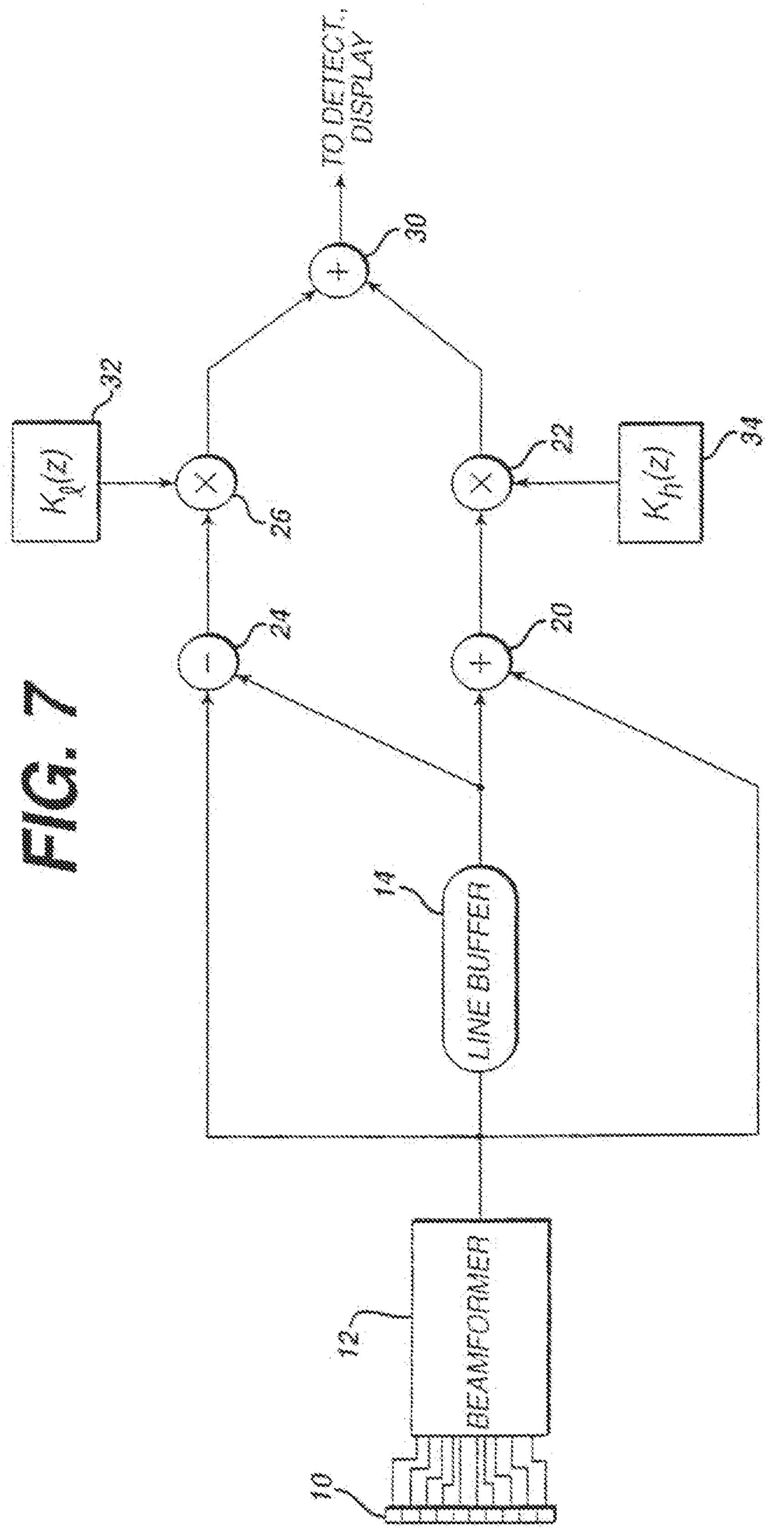

TO DETECT., DISPLAY
30
$K_l(z)$
32
26
22
$K_h(z)$
34
24
20
LINE BUFFER
14
BEAMFORMER
12
10

FIG. 8

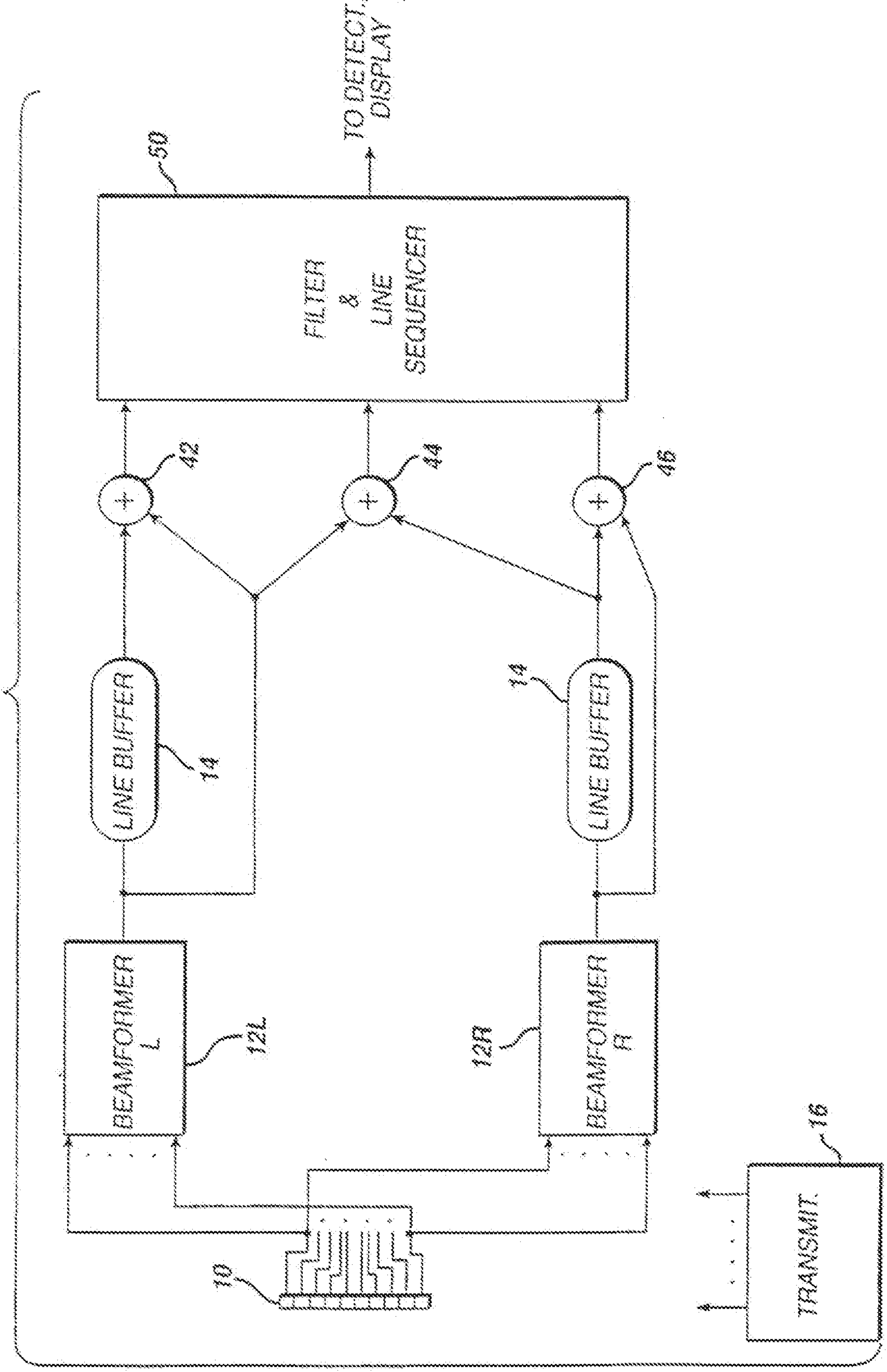
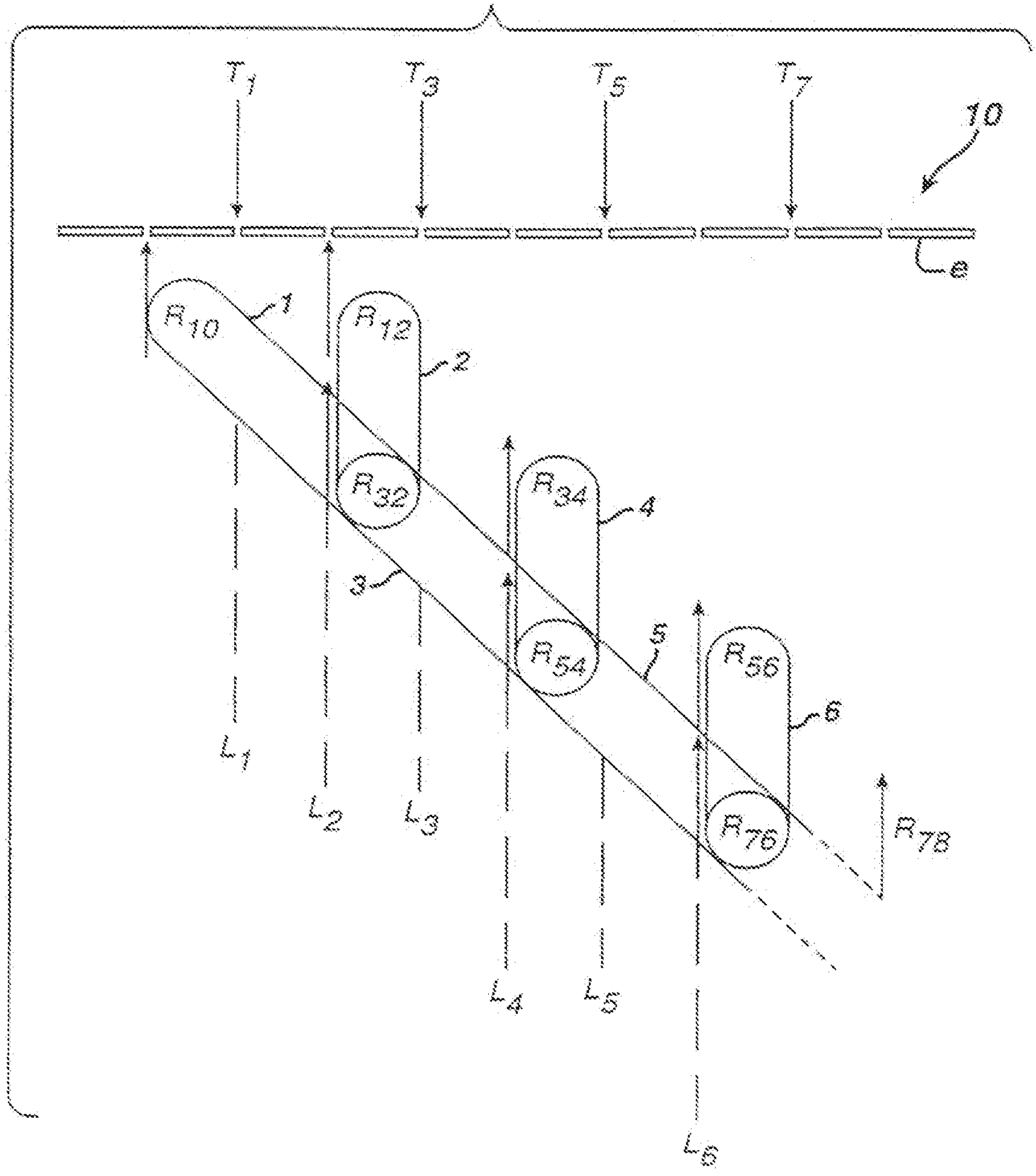

TO DETECT, DISPLAY
50
FILTER & LINE SEQUENCER
42
44
46
LINE BUFFER
14
LINE BUFFER
14
BEAMFORMER L
12L
BEAMFORMER R
12R
10
TRANSMIT.
16

FIG. 9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T3
T5
T7
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e
R10
1
R12
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R32
R34
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R54
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L3
R76
R78
L4
L5
L6

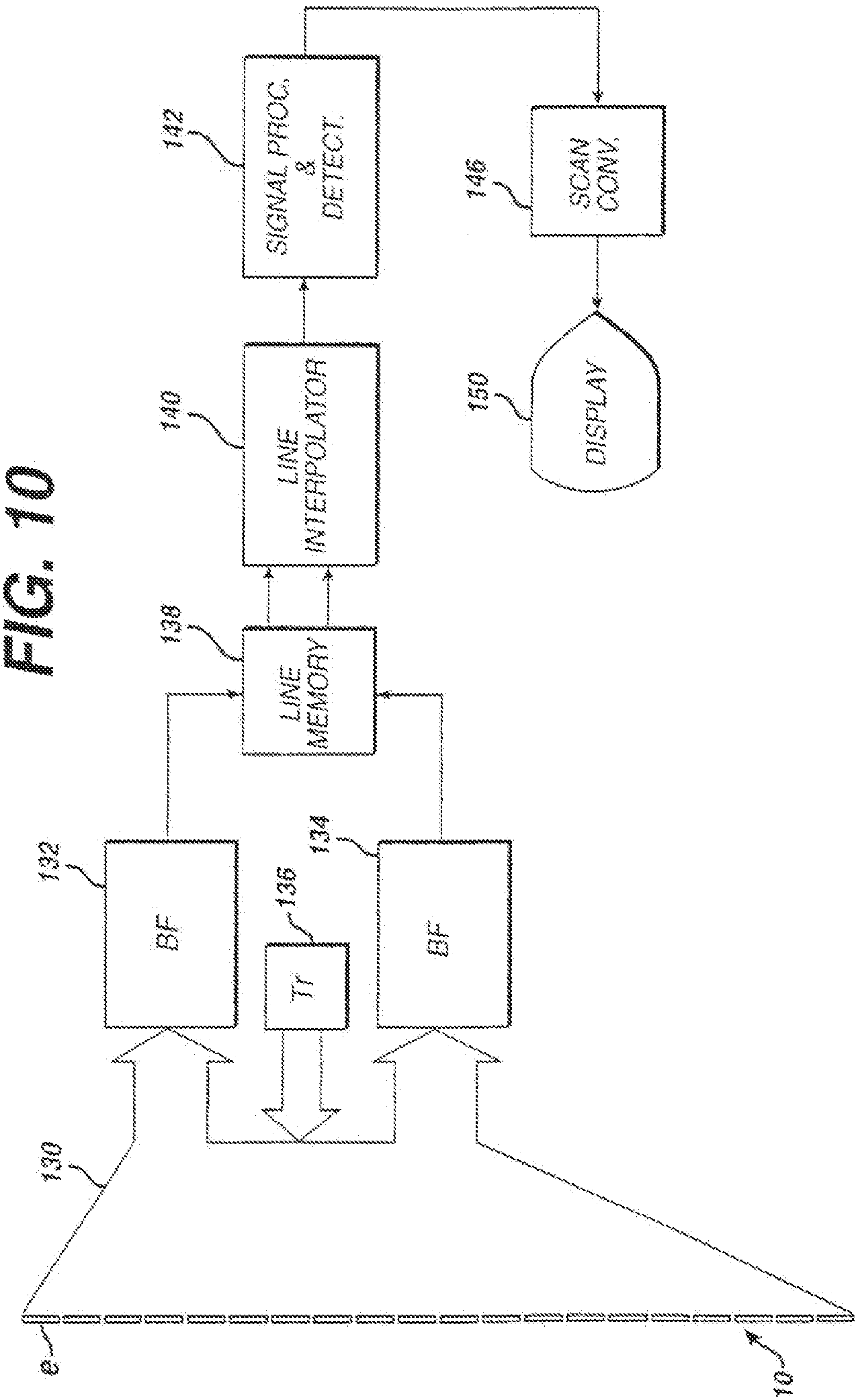
SIGNAL PROC. & DETECT.
142
SCAN CONV.
146
DISPLAY
150
LINE INTERPOLATOR
140
LINE MEMORY
138
BF
132
Tr
136
BF
134
130
e
10

FIG. 10

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 00/00214

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G01S15/89

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 678 552 A (SAVORD BERNARD J) 21 October 1997 (1997-10-21) * Summary of the Invention * figure 3	1-5,8-10
A	column 11, line 51 -column 16, line 24	6,7,11, 12
A	US 5 390 674 A (ROBINSON BRENT S ET AL) 21 February 1995 (1995-02-21) column 2, line 16 - line 28 column 3, line 47 - line 61 column 5, line 18 - line 39	1-12

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 June 2000	03/07/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ó Donnabháin, C

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/EP 00/00214

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		DE 4345379 C	02-04-1998
		DE 4345380 C	26-03-1998
		DE 4345381 C	16-04-1998
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